Department of Mechanical and Nuclear Engineering
Department of Materials Science and Engineering

INFLUENCE OF HYDRIDE DISTRIBUTION ON FAILURE OF ZIRCALOY-4 SHEET

Olivier Pierron, R.S. Daum, D.A. Koss, A.T. Motta, and K.S. Chan

Funded by the Fermi Consortium

NSRC, October 28-30, 2002

Department of Mechanical and Nuclear Engineering
Department of Materials Science and Engineering

Industrial Context

- Nuclear Industry wants to **increase fuel burnups** (residence time in reactor):
  - Fuel savings; longer fuel cycles, => higher capacity factor
  - Reduction in waste volume (less fuel assemblies for same power produced)
- Increased burnup => increased radiation damage, but also increased oxidation and associated hydriding of cladding
- **Problem**: can highly hydrided Zircaloy-4 cladding withstand severe loading conditions associated with postulated licensing accidents? (i.e., is it safe to operate fuel at high burnup, what are the limits?)

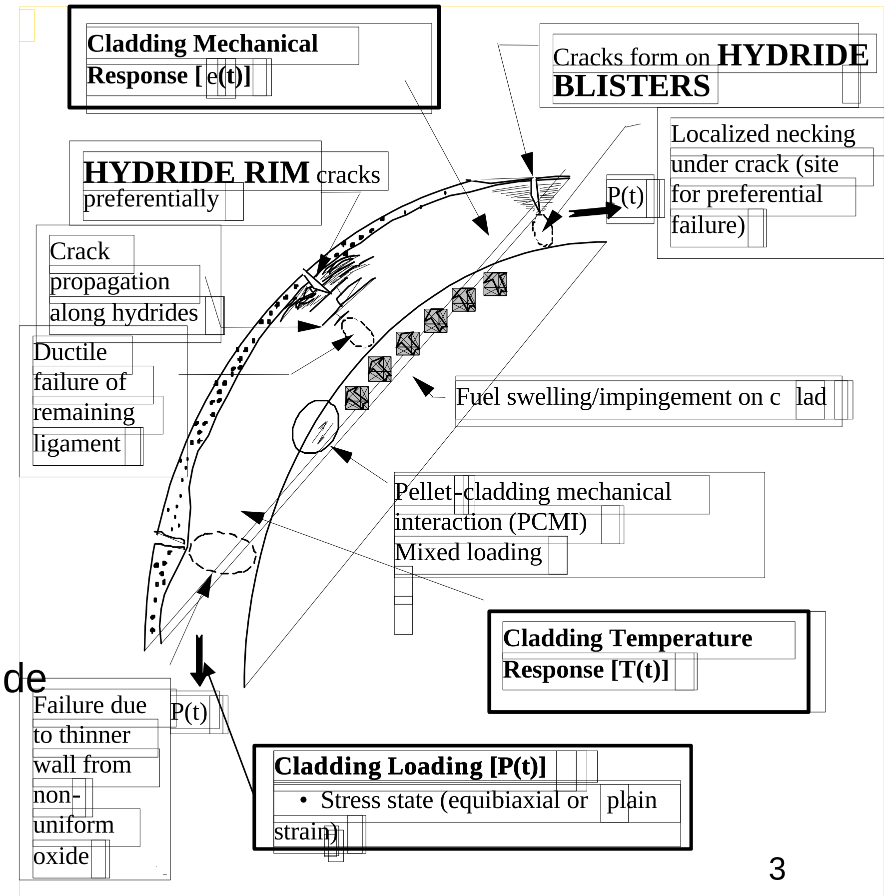
PENNSTATE
Department of Mechanical and Nuclear Engineering
Department of Materials Science and Engineering

Effect of Hydrogen

- H affects cladding behavior.
- Two H distributions:
  - **Hydride “rim”** (temperature gradient from heat flux during operation)

    ⇒ Ινϖεστιγατεδ (PSU)
  - **Hydride “blister”** (oxide spalling creates local “cold” spots where H aggregates)

    ⇒ Τηισ στυδψ



PENNSTATE
Department of Mechanical and Nuclear Engineering
Department of Materials Science and Engineering

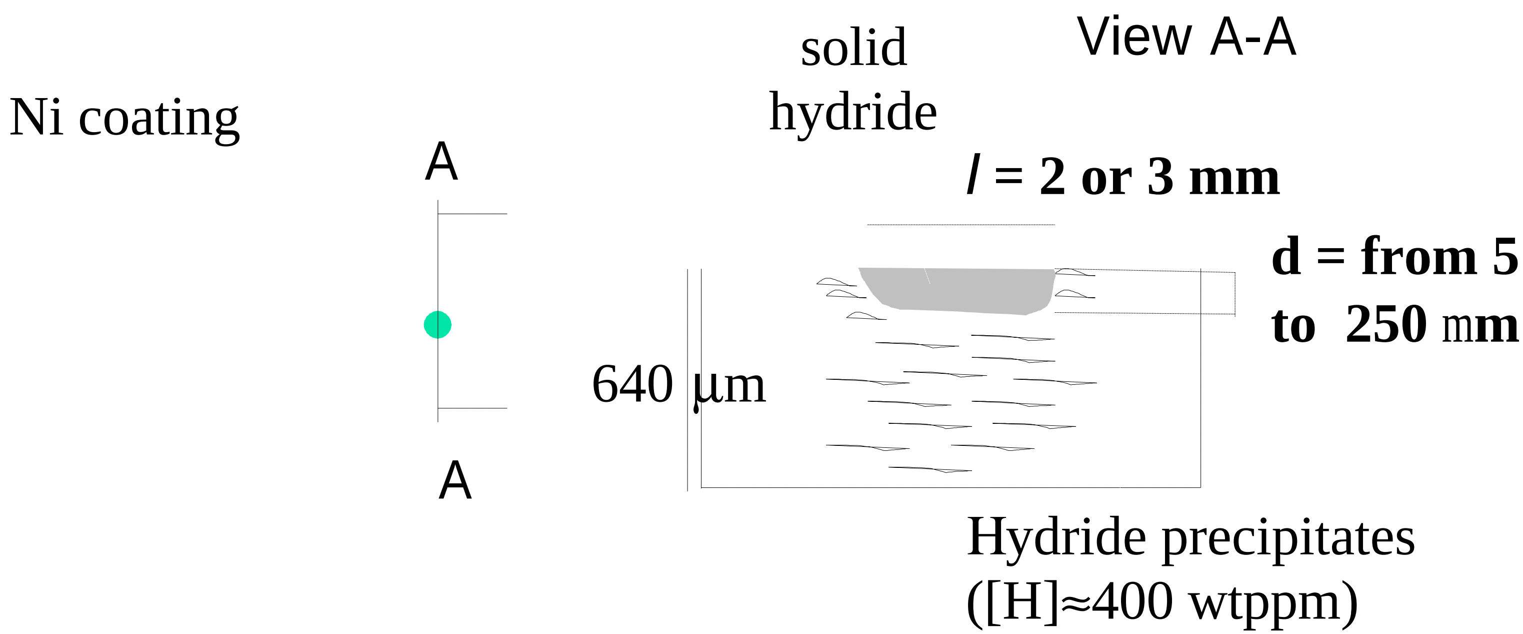
This Study: Hydride “Blisters”

- Experimental procedure:
  - Developed a new procedure that **simulates** the presence of hydride blisters on unirradiated Zircaloy-4 flat sheet with texture similar to tube.
  - **Plane-strain tension** (multi-axial stresses).
  - Two testing temperatures: **25°C**, **300°C**.
  - Two materials: **RX**, **CWSR**.

PENNSTATE
Department of Mechanical and Nuclear Engineering
Department of Materials Science and Engineering

Hydride Blister Formation

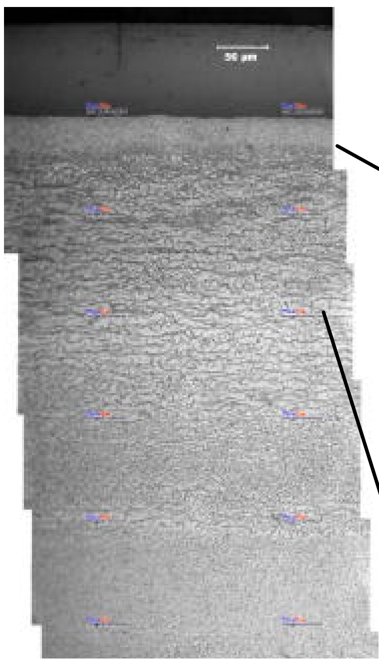
- Gas charging at 400°C

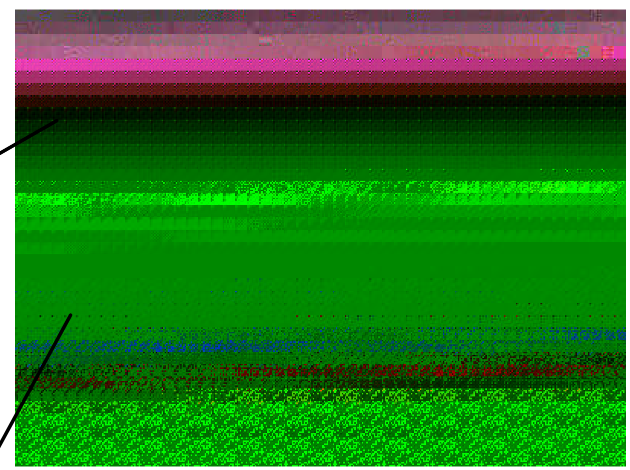


Department of Mechanical and Nuclear Engineering
Department of Materials Science and Engineering

Comparison with Cladding

- **Irradiated cladding** (av. fuel burnup of 67 GWd/t and fast fluence of 1.3×10^{22} n/cm^2)
- **PSU Hydriding** (H_2 gas charging at 400°C)

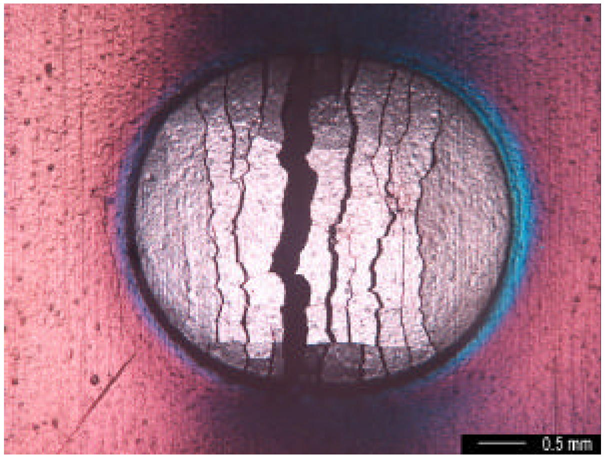




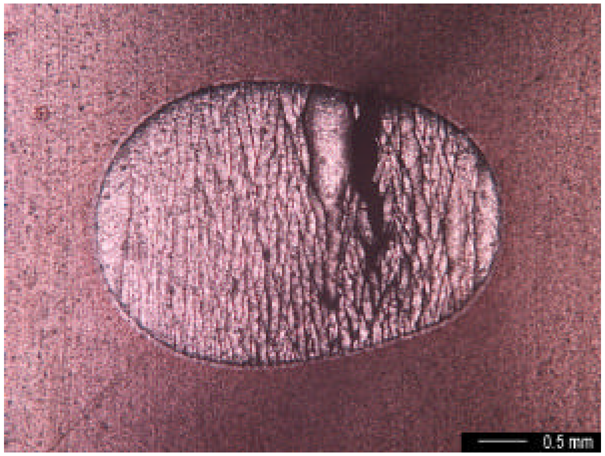
Department of Mechanical and Nuclear Engineering
Department of Materials Science and Engineering

Fracture of "Blisters"

- Formation of **micro-cracks** upon yielding (detected by Acoustic Emission).



Blister Depth: 215 µm



Blister Depth: 40 µm

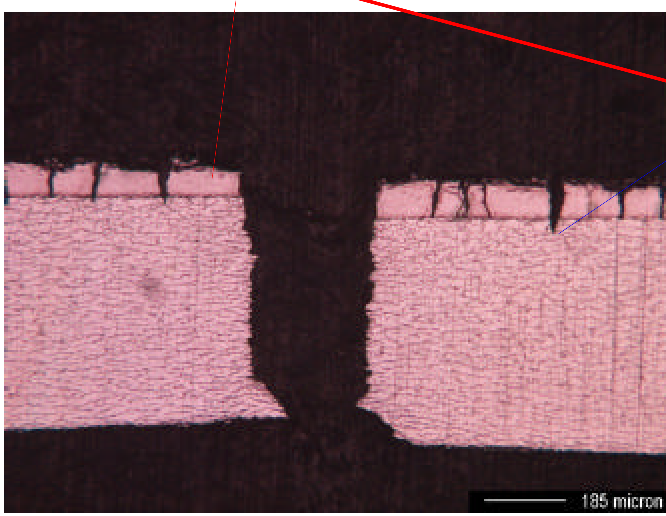
PENNSTATE
Department of Mechanical and Nuclear Engineering
Department of Materials Science and Engineering

Fracture Profiles

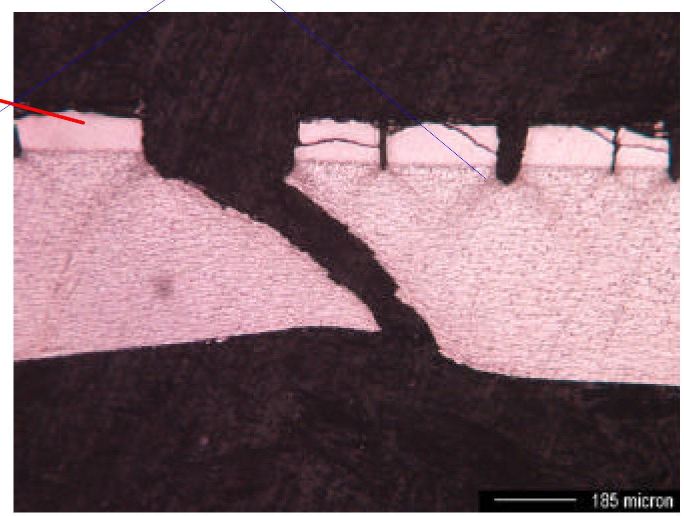
- *Crack Growth vs. Shear Instablility*

Hydride Blister

Arrested micro-cracks



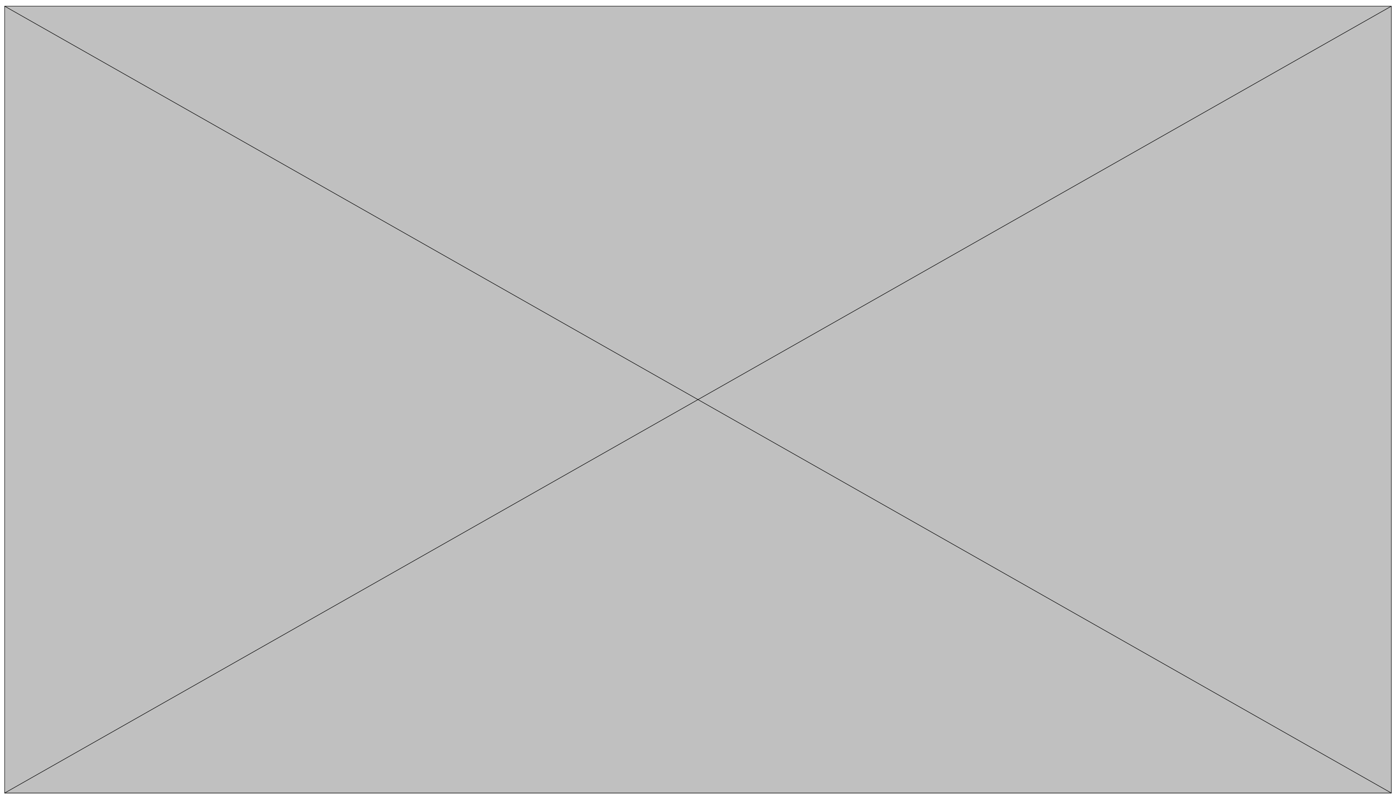
25°C



300°C

PENNSTATE
Department of Mechanical and Nuclear Engineering
Department of Materials Science and Engineering

Specimen Ductility



PENNSTATE
Department of Mechanical and Nuclear Engineering
Department of Materials Science and Engineering

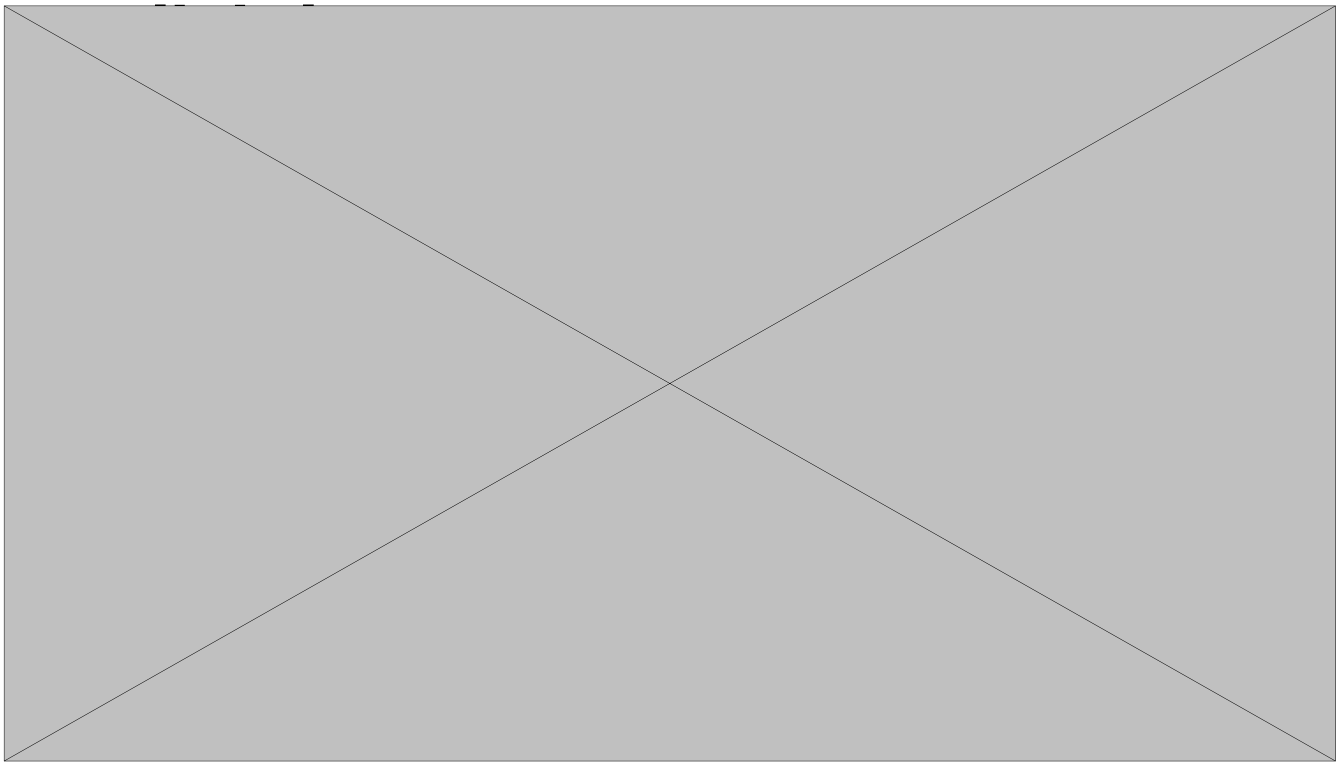
Specimen Ductility

- Significant decrease in ductility at 25°C w/ increasing blister depth > 25-50µm and plateau beyond ≈120µm.
- Similar ductility between 2-mm and 3-mm diameter blisters.
- Hydrogen embrittlement less severe at 300°C than at 25°C for given blister depth.

PENNSTATE
Department of Mechanical and Nuclear Engineering
Department of Materials Science and Engineering

Specimen Ductility

- Blister vs Rim for CWSR at 25°C⇒ **Rim**



PENNSTATE
Department of Mechanical and Nuclear Engineering
Department of Materials Science and Engineering

Summary of Results

Zircaloy w/ 2 or 3 mm-diameter blisters (5 to 250μm thick) + hydride precipitates in substrate

- Blisters crack upon yielding.
- As blister depth ↑ φραχτυρε στραιν ↓ (roughly independent of blister width)
- For given blister depth:

$$(\varepsilon_{frac})_{RX,25} \approx (\varepsilon_{frac})_{CW,25} < (\varepsilon_{frac})_{CW,300} < (\varepsilon_{frac})_{RX,300}$$

PENNSTATE
Department of Mechanical and Nuclear Engineering
Department of Materials Science and Engineering

Summary of Results

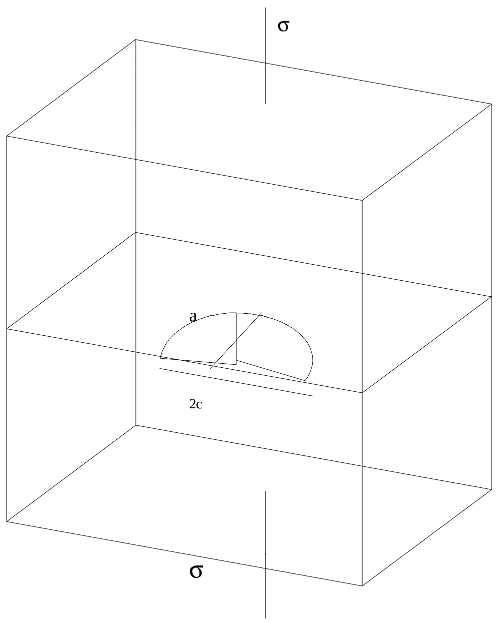
- Fracture of sheet / cladding controlled by failure of substrate below blister:
  - At 25°C: crack growth on plane normal to σ_1.
  - At 300°C: shear instability on plane 45° to σ_1.
- Can we **predict** these results?
  - 25°C----fracture mechanics analysis
  - 300°C---analysis is still incomplete

PENNSTATE
Department of Mechanical and Nuclear Engineering
Department of Materials Science and Engineering

Fracture Mechanics Analysis

- Assumptions:
  - Single crack w/ depth = blister depth
  - Through-thickness plane stress conditions
  - J-integral procedure
  - Plastic zone correction
- Fracture occurs when:

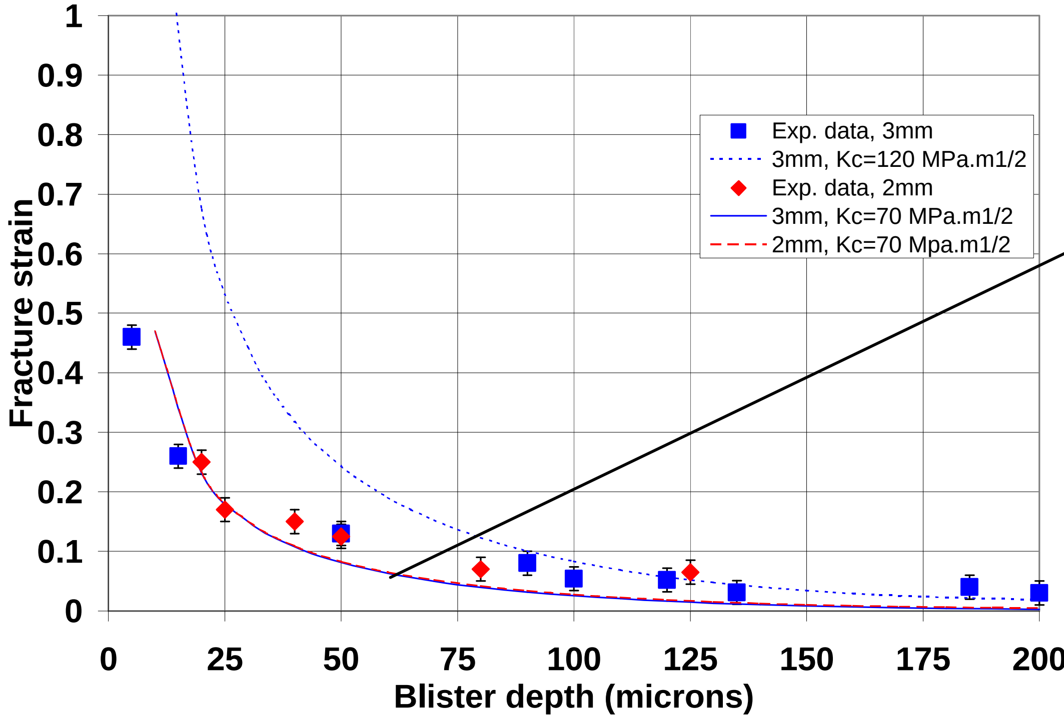
$$\varepsilon_n^p = \alpha \frac{\sigma_0}{E}\left\{\frac{1}{\alpha}\left(\frac{K_c^2}{K_e^2} - 1\right)\right\}^{\frac{n}{n-1}}$$



PENNSTATE
Department of Mechanical and Nuclear Engineering
Department of Materials Science and Engineering

Fracture Mechanics Analysis

- CWSR material at 25°C with two levels of fracture toughness:



Modeling **similar** for 2mm and 3mm wide cracks

PENNSTATE
Department of Mechanical and Nuclear Engineering
Department of Materials Science and Engineering

Fracture Mechanics Analysis

- At 25°C, fracture mechanics predicts exp. results for a reasonable Kc≈70 MPa.m$^{1/2}$, in accordance with fracture profile (crack propagation).
- At 300°C, fracture toughness ↑ ανδ φαιλυρε occurs by **competing mechanism** ⇒**shear instability** (fracture mechanics no longer applies)

PENNSTATE

Department of Mechanical and Nuclear Engineering
Department of Materials Science and Engineering

Summary

Zircaloy w/ 2 or 3 mm-diameter blisters (5 to 250μm thick) + hydride precipitates in substrate

- Blisters crack upon yielding.
- As blister depth ↑ φραχτυρε στραιν ↓ (ρουγηλψ independent of blister width, $(K_I)_{2mm} \approx (K_I)_{3mm}$)
- For given blister depth:

$$(\varepsilon_{frac})_{RX,25} \approx (\varepsilon_{frac})_{CW,25} < (\varepsilon_{frac})_{CW,300} < (\varepsilon_{frac})_{RX,300}$$

PENNSTATE
Department of Mechanical and Nuclear Engineering
Department of Materials Science and Engineering

Summary

- Fracture of sheet / cladding controlled by failure of substrate below blister:
  - At 25°C: crack growth on plane normal to σ_1 (predicted for $K_c \approx 70$ ΜΠα.μ$^{1/2}$).
  - At 300°C: shear instability on plane 45° to σ_1.
- Fracture of substrate depends on ease of void nucleation at hydrides. At 25°C, hydrides crack / voids coalesce. Not so at 300°C where $(\varepsilon_N)_{300} > (\varepsilon_N)_{25}$ and shear instability develops.